Low-ionization structures in planetary nebulae: confronting models with observations

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ABSTRACT

Around 50 planetary nebulae (PNe) are presently known to possess "small-scale" low-ionization structures (LISs) located inside or outside their main nebular bodies. We consider here the different kinds of LISs (jets, jet-like systems, symmetrical and non-symmetrical knots) and present a detailed comparison of the existing model predictions with the observational morphological and kinematical properties.

We find that nebulae with LISs appear indistinctly spread among all morphological classes of PNe, indicating that the processes leading to the formation of LISs are not necessarily related to those responsible for the asphericity of the large-scale morphological components of PNe.

We show that both the observed velocities and locations of most non-symmetrical systems of LISs can be reasonably well reproduced assuming either fossil condensations originated in the AGB wind or in situ instabilities.

The jet models proposed to date (hydrodynamical and magnetohydrodynamical interacting winds or accretion-disk collimated winds) appear unable to account simultaneously for several key characteristics of the observed high-velocity jets, such as their kinematical ages and the angle between the jet and the symmetry axes of the nebulae. The linear increase in velocity observed in several jets favors magnetohydrodynamical confinement compared to pure hydrodynamical interacting wind models.

On the other hand, we find that the formation of jet-like systems characterized by relatively low expansion velocities (similar to those of the main shells of PNe) cannot be explained by any of the existing models.

Finally, the knots which appear in symmetrical and opposite pairs of low velocity could be understood as the survival of fossil (symmetrical) condensations formed during the AGB phase or as structures that have experienced substantial slowing down by the ambient medium.

Subject headings: planetary nebulae - ISM: kinematics and dynamics - ISM: jets and outflows

1. Introduction

The most accepted scenario for the formation of a planetary nebula (PN) is that originally proposed by Kwok, Purton & Fitzgerald (1978), the so called interacting stellar wind (ISW) model. ISW models are successful at predicting the formation and properties of the main morphological components of PNe (Kwok 1994; Mellema 1995), such as bright rims, attached shells and the haloes that characterize spherical and elliptical PNe. These main structures are better identified in the light of hydrogen and helium recombination lines, as well as in the forbidden [O III] lines. But, on usually smaller scales, there are also structures which are instead more prominent in low-ionization lines, such as [N II], [O II], [O I] and [S II]. They have often been grouped under the general denomination of "small-scale low-ionization structures" of PNe. These low-ionization structures (hereafter we use the acronym LISs [1]) have received more and more attention after the imaging catalogues of Balick (1987), Schwarz, Corradi & Melnick (1992), Manchado et al. (1996), Górny et al. (1999) and the compilation by Corradi et al. (1996), the latter particularly devoted to low-ionization structures.

Observationally, LISs appear with a variety of morphologies: knots, tails, filaments, jets and jet-like structures of low ionization attached to, or detached from, the main shells of the nebulae. They are sometimes labeled with specific acronyms intending to describe some of their physical characteristics – for instance, FLIERs (fast, low-ionization emission regions; Balick et al. 1993); or BRETs (bipolar, rotating, episodic jets; López, Vázquez, & Rodríguez 1995).

On the theoretical side, different models have been proposed to explain the origin of LISs. The main ones are: ISW models (Frank, Balick, & Livio 1996; García-Segura et al. 1999); jet formation and its interaction with the circumstellar medium (Cliffe et al. 1995; Redman & Dyson 1999), and the interaction of shells with the interstellar medium (Soker & Zucker 1997). In addition, other ingredients – such as stellar magnetic fields, rotation, precession, a binary system in the center, and dynamical (Kelvin–Helmholtz and Rayleigh–Taylor) and/or radiation instabilities – are sometimes considered within these models in order to explain the observations. In spite of this theoretical effort, the nature of LISs in PNe is still poorly understood.

In the following sections, we present a comprehensive compilation of the observations of LISs in PNe (focusing on morphological and kinematical data) and discuss their different properties with the aim of confronting the various theoretical models proposed to explain their formation. The motivation for this study is presented in Section 2. In Section 3, we present the PNe sample. Section 4 is devoted to jet and jet-like LISs, Section 5 to symmetrical knots, and Section 6 to non-symmetrical LISs. A final discussion on LISs showing multiple pairs of LIS is presented in Section 7, and the main conclusions are summarized in Section 8.

2. Motivation

Low-ionization small-scale structures potentially contain important information about the mass loss and radiative processes that lead to the formation and development of a plane-

[1] The acronymous LIS is used here only for the sake of conciseness, with no intention of adding a new term to the already very rich nomenclature used for PNe (see Schwarz 2000).

tary nebula. Recently, we have obtained morphological and kinematical data for nine PNe (Corradi et al. 1997, 1999, 2000a, 2000b) with the aim of studying the physical properties, origin and evolution of the LISs therein contained. Results are both promising and puzzling since we have found LISs with notably different properties relative to each other, in terms of expansion velocities, shapes, sizes and locations relative to the main nebular components. It appears that several physical processes have to be considered in order to account for the formation and evolution of all the different LISs that we observed.

In particular, the following basic questions are open. Are magnetic fields – either in single or binary stars – necessary for producing jets in PNe, as generally believed for young stellar objects and active galactic nuclei jets? Which processes, even in complex systems like interacting binary stars, can produce multiple systems of highly collimated outflows expanding in directions almost perpendicular to each other as observed in some PNe? How do low-velocity collimated LISs form? Are symmetric pairs of knots recent ejecta from the central stars, or fossil condensations tracing a peculiar mass-loss geometry during the AGB? Are non-symmetrical LISs formed by in situ instabilities?

Taking advantage of our recent work and of the information which is spread throughout the literature, we carefully address these points in what follows.

3. The sample of PNe with LISs

3.1. Morphological/kinematical classification for LISs

In this paper, we adopt a working definition of LISs as features especially prominent in low-ionization lines (the most commonly observed is [N II]), and which have a size, at least in one direction, much smaller than the main morphological components of the PNe, namely the main shells and haloes of elliptical PNe, or the lobes of bipolar PNe. In spite of this definition, it should be noted that, in some cases, LISs can form large structures which can extend to few parsecs, such as the string of knots which define the point-symmetrical collimated outflow of Fg 1 (Palmer et al. 1996).

Due to the variety of LISs found, some further definition of the terms used in the following is in order. Hereafter we refer to as *knots* all unresolved LISs, as well as all resolved small-scale low-ionization features with an aspect ratio (maximum length to maximum width) close to 1. All features with an aspect ratio much larger than one are instead called *filaments*. Knots and filaments appear with any orientation with respect to the central star, and not necessarily in pairs.

Jets are a more restrict subclass of highly collimated filaments, which i) are directed in the radial direction from the central star, ii) appear in opposite symmetrical pairs and iii) move with velocities substantially larger than those of the ambient gas which form the main bodies of the nebulae. Finally, all features resembling jets, but for which no evidence exists that are expanding significantly more rapidly than the ambient gas (in many cases, because of lack of information and/or appropriate modeling) are called *jet-like* structures. It is clear that projection effects, which are often poorly known, play a fundamental role in distinguishing genuine jets from jet-like LISs.

In our classification, ansae (Balick 1987) and FLIERs (Balick et al. 1993) are pairs of knots, whereas BRETs (López et al. 1995) are pairs of knots or jets, with a point-symmetrical distribution.

With these definitions in mind, and aiming at a more comprehensive analysis of the properties of LISs than has been attempted in the past, we have added to our observational sample all the data that we were able to recover from the literature, building up a final sample of 50 PNe containing LISs. These are listed in Table 1, together with the designations for the PNe and the morphology of the main nebular shell. The fourth column in Table 1 contains the classification of the LISs. The references from which the properties of the nebulae were taken are given in the last column of the Table.

3.2. LISs frequency vs. PN morphological type

In the third column of Table 1, we give the morphological classification of the PNe following the scheme of Schwarz, Corradi & Stanghellini (1993), based on optical narrowband images. Extended PNe are classified into four main classes: elliptical (E), bipolar (B), point-symmetric (P) and irregular (I).

In our sample, we find 29 elliptical PNe (58%), seven bipolars (14%), nine point-symmetrics (18%) and three irregulars (6%). Two PNe (K 4-47 and IC 2149) were not classified since they do not easily fit into any of the above classes. These figures can be compared with those for the global sample of PNe. Corradi & Schwarz (1995) classified 359 PNe, finding 64% ellipticals, 14% bipolars, 4% point-symmetrics, and 18% irregulars. Thus, LISs appear indistinctly in elliptical and bipolar objects compared to the general sample of PNe, but seem to be more frequent in point-symmetrical objects. The latter result, however, is probably related to the definition itself of this class of PNe, whose characteristic symmetry is generally defined by the presence of small-scale structures. Irregulars are much less frequent in our sample than in the general one, probably because new observations allow a better classification of these objects.

We therefore conclude that low-ionization structures are spread throughout the morphological classes of PNe indistinctly. Such a result would indicate that the formation of LISs is not necessarily connected with the processes responsible for the asphericity in PNe (whatever they are).

4. Jets and jet-like LISs

4.1. Theories for the formation of collimated LISs

To allow for a critical discussion of the most relevant observational properties of jets in PNe, a brief review of jet formation models is presented here.

Interacting stellar wind (ISW) theories, in addition to explaining the formation of the main morphological components of PNe, can, under certain conditions, account for the formation of highly collimated LISs. The first ISW model for jet formation (Icke et al. 1992) was able to produce moderately collimated structures by inertial confinement starting from a torus-like density contrast in the mass distribution of the AGB wind. Subsequently, it became clear that the transition from the slow to the fast wind (the so called momentum-driven phase in the early evolution of a PN) also plays an important role in the confinement (cf. Frank et al. 1996). Nowadays, ISW models consider in detail the evolution of the fast wind in velocity and mass loss (Dwarkadas & Balick 1998), resulting in considerably more structure on smaller scales than in the models in which the fast wind velocity is assumed to be constant. In addition to jet formation, the momentum-driven phase leads to instabilities (thin-shell Vishniac instabilities and Kelvin–Helmholtz instabilities) which may be the origin of knots and filaments. Later in the evolution, during the energy-driven phase, other instabilities, such as Rayleigh–Taylor ones, can also appear, modifying the structures formed in the previous phase (Breitschwerdt & Kahn 1990; Dwarkadas & Balick 1998; García-Segura et al. 1999). The above ISW models, based on a single-star scenario for PN/jet formation, consist of hydrodynamical (HD) simulations (Mellema & Frank 1997; Borkowski, Blondin, & Harrington 1997; in addition to the papers cited above) or consider the presence of a magnetized stellar wind (MHD simulations; Różyczka & Franco 1996; García-Segura 1997; García-Segura et al. 1999).

As commented previously, a key parameter for HD collimation is the equator-to-pole density contrast of the AGB wind. Even if HD ISW models are able to account for the jet formation, the question of the source of that asphericity in the AGB wind remains open; the most popular models consider that the central star is part of a binary system (Morris 1987; Mastrodemos & Morris 1999; see also Soker & Livio 1994 and Livio & Pringle 1997, for the formation of accretion-disks around the PN central star). In this way an accretion-disk and possibly also an "excretion" disk can be formed and later used for collimating the jet, as well as for shaping the PNe. On the other hand, in the MHD ISW models presently available, the non-spherical density distribution in the AGB wind is the direct result of stellar rotation, which, together with the magnetic tension, produces aspherical shells and highly collimated jets.

The ISW simulations specifically predict certain important properties that can be compared with the observations. Firstly, the jets formed i) are two-sided highly collimated structures, ii) possess supersonic velocities much larger than those of the main shells, iii) are roughly coeval with the main shell, and iv) lie along the major symmetry axis of the PNe (unless precession of the center star is considered, in which case point-symmetric jets are formed). Secondly, when a magnetic field is taken into account, the expansion velocity of the jets is expected to increase linearly outwards (García-Segura et al. 1999). Finally, depending on the kind of collimation mechanism assumed, the jets may appear only outside the main shell (pure HD confinement) or also inside it (MHD collimation).

As an alternative to the standard ISW theory, some models consider the possibility that high-velocity, highly collimated jets in PNe are directly produced by the accretion-disks, which result from the interaction between the central star of a PN (or its progenitor) with a secondary. Most studies consider that the jet forms immediately after the common-envelope phase of a close binary system (Soker 1992, 1996; Soker & Livio 1994; Reyes-Ruiz & López 1999). However, the evolution from the common-envelope phase up to the jet formation has not been investigated in detail. Mastrodemos & Morris (1998, 1999) consider the formation of accretion-disks in long-period binaries, thereby avoiding the common-envelope phase.

In a different context, it seems clear now that the formation of highly collimated, powerful jets, both in young stellar objects and in active galactic nuclei, requires two main ingredients: an accretion-disk and a vertical magnetic field (Livio 1997, 2000). Very recently, Blackman et al. (2000) proposed an MHD model for the interplay of stellar and disk winds which constrains the stellar and disk rotation and the magnetic fields in order to account for multiple bipolar outflows, either bipolar lobes or highly collimated jets.

In general, jets emerging from accretion-disks arise before[2] the formation of the PN main shell. Typical velocities are several hundred $\mathrm{km\,s^{-1}}$, whereas their orientation depends on the angle between stellar and disk rotational (and magnetic) axes, i.e., they are not necessarily aligned with the nebular symmetry axis (Blackman et al. 2000). Depending on the stage of evolution of the primary, these accretion-disk jets are expected to be found outside or inside the bright rims.

Finally, precession of jets within 3D simulations (Cliffe et al. 1995; García-Segura 1997) is the natural way to account for the point-symmetry in PNe and in their LISs. Note that Cliffe et al. (1995) describe the interaction of a precessing jet with the circumstellar medium, regardless of the jet formation mechanism.

4.2. Observational properties of jets

We present in Table 2 the list of the 12 known low-ionization jets. In this table, column 2 gives a (subjective) confidence index which reflects the quality of the available observational data and spatio-kinematical modeling performed. Their approximate kinematical ages (compared to that of the main nebular shell), the angle between the jet and the nebular symmetry axis, and their location inside or outside the bright shell of the PNe which is expected to define the fast vs. slow wind interaction region, are also given in Table 2.

As already stated, a basic prediction of the ISW models, within the single-star scenario, is that the jets have to be roughly coeval with the main nebula. This is true for four objects in Table 2 (NGC 7009, NGC 6891, NGC 6884 and NGC 3918). Three others (M 1-16, Fg 1 and K 4-47) are older than the main nebulae and would be better understood within the accretion-disk models. But the remaining three objects for which this information is available have smaller kinematical ages than their PNe and cannot be accounted for by any of these models.

In addition, it is clear that, at variance with the predictions of the ISW models, only two jets (over eight objects with adequate data) lie along the polar axis of the main nebula. When the jet–nebula axis angle is relatively small, either stellar or disk precession might explain the observed orientation of the jet. However, for very large angles (from 50° in NGC 6884 to the extreme "equatorial" jets of Hb 4 and possibly NGC 6210), the kind of extreme disk precession and wobbling described by Livio & Pringle (1997) would be needed, but that is expected to occur only during a very short phase of the disk evolution (see Cox et al. 2000 and Sahai et al. 2000, on the direct evidence for highly-collimated jets close to the equatorial plane in the protoplanetary nebulae CRL2688 and Frosty Leo, respectively).

For all but one of the objects in Table 2 for which detailed kinematical information is available (NGC 3918, He 2-186, K 4-47, Fg 1,

[2] A few peculiar, iron-deficient post-AGB stars in close binaries show circumstellar disks fuelled by back-accretion during the post-AGB evolution (Van Winckel et al. 1999). In principle, such disks could produce jets *after* the formation of the PN main shell.

M 1-16, NGC 6543 and NGC 6891) the jets show a roughly linear increase in expansion velocity with distance in the radial direction, as if they consisted of material ejected by the central star with a range of velocities during a relatively short burst. Among the models discussed above, only the MHD ISW models (García-Segura et al. 1999) predict this velocity behavior, favoring the latter ones compared to the pure HD models. The location outside the nebular rims of all the jets in Table 2, instead, does not help in distinguishing between the different models.

In summary, it appears that the single-star HD and MHD ISW models are able to explain only some of the observed jets, the latter models being favored by the observed roughly linear increase of velocities with distance from the central stars. Three objects are instead better understood as accretion-disk jets, but still almost one half of the sample shows unexpected properties, in terms of ages or jet–nebulae axis angle. These objects are a real challenge to the ideas on jet formation and clearly deserve future theoretical and observational studies.

4.3. Jet-like features

The list of jet-like LISs is presented in Table 3. For three objects, the available morphological and kinematical data do not allow us to disentangle projection effects and determine the basic properties of the main nebulae and jets (orientation and deprojected expansion velocities), and we will not discuss these objects further. But for six PNe (IC 4593, He 2-429, NGC 6881, K 1-2, Wray 17-1, and likely NGC 6751), observations have shown that their jet-like LIS really expand with velocities similar, or at least not significantly larger, than those of the ambient gas that forms the large-scale shells of the nebulae. This is rather embarrassing, because all models for the formation of highly collimated structures predict high-velocity systems[3]. In fact, in spite of the unexpectedly low velocities, jet-like LISs present many similarities with real jets — they are commonly two-sided highly collimated structures, radially or point-symmetrically distributed.

It is interesting to ask if jet-like LIS also present an increasing velocity outwards, as the real jets do. There are only two cases where adequate information exist: K 1-2 and Wray 17-1 (Corradi et al. 1999). In the case of K 1-2, the velocity increases linearly as the collimated and knotty structure protrudes from the edge of the main nebular shell. From there, some acceleration is expected because of the lower density of the outer ambient material. Thus, the peculiar behavior of the LIS's velocity in the external regions could just be a consequence of the density stratification of the ambient gas, and not related to the LIS formation process itself. The jet-like LIS of Wray 17-1, on the other hand, displays low radial velocities through almost the entire structure except for its outermost tail. This suggests that the tail might not be physically related to the innermost parts of the LIS, but is instead most probably an ionization effect, i.e., a lower-ionization region shielded from energetic photons from the central star by the inner, higher-ionization patch. The large velocities found at the tail would just represent the general motions of the outer regions of the PN.

The two cases above are complex and warn us of the danger of simplistic and general ex-

[3]Note that the "low-velocity jets" described in Soker (1992) are expected to disappear before the formation of the PN shell.

planations. The fact that the other jet-like LISs are all found outside the rims and have low velocities and high collimation is puzzling. None of their characteristics gives us clear indications about the processes that could collimate these systems. Jet-like LISs are hardly understood at present.

5. Pairs of knots

5.1. Theories

Jet formation models can also be applied to low-ionization knots which appear in pairs, because knots and filaments along the jets and at their tips can develop during the evolution of the jet itself, as a consequence of kink, Vishniac, Rayleigh–Taylor or Kelvin–Helmholtz instabilities (c.f. García-Segura et al. 1999). One may ask why we do not see the whole jets in such systems. There are two obvious possibilities: the jet does not exist any longer, or has properties which make it difficult to observe. In fact, Soker (1990) proposed that jets formed by disks are the prime cause of pairs of knots, and showed that, under certain conditions, the jets can be seen only in the early stages of the PN evolution, but have cool heads which appear as more permanent features. In a different context, García-Segura (1997) argued that a weak radiative cooling in the post-shock gas, imposed by the wind conditions, also results in the formation of pairs of knots instead of extended jets.

A different model to explain the formation of symmetrical knots is that they arise in the concave section of bow-shocks – i.e. knots would develop in the stagnation zones of partially collimated stellar winds (as cool dense portions of gas accumulates in these regions) aligned with the symmetry axis and attached to the shell (Steffen & López 1998, 2000). In this case high-velocity pairs of knots directed along the polar axis of the asymmetrical shell are expected.

Finally, it is important to note that all high-velocity knots (FLIERs) imaged by the *HST* (Balick et al. 1998) do not show the outward-facing bow-shocks expected to develop due to the supersonic velocity of the knots, in apparent contradiction with all the above models. However, Soker & Reveg (1998) argue that bow-shocks are not expected when the density contrast between the knot and the ambient medium is moderate, because instabilities which occur at the knots' surface may considerably change their geometry, and form extreme outward-pointing tail structures instead of bow-shocks (see also Jones, Kang & Tregillis 1994).

5.2. Observed properties

PNe which present symmetrical pairs of low-ionization knots are listed in Table 4. Note that some objects are also in Table 2 or Table 3, because some PNe show more than one type of LIS (see fourth column of Table 1). Hb 4, for instance, has a jet-like pair as well as a pair of knots (Corradi et al. 1996; Hajian et al. 1997; López, Steffen & Meaburn 1997).

The third column of the Table 4 indicates whether the knots have peculiar velocities with respect to the ambient gas. Note that nine PNe in this table possess high-velocity knots, like the well studied FLIERs (Balick et al. 1998), but only five of them are clearly in the polar direction. These two properties would indicate that the pairs of knots in NGC 7009, Hu 2-1, NGC 6905, NGC 6826 and Kj Pn 8 could be either the leading front of unobserved jets or produced at the wind's stagnation zones.

Six PNe in Table 4 (IC 4593, He 1-1, NGC 2440, Wray 17-1, IC 2553 and NGC 5189) contain pairs of knots with velocities similar to those of the ambient gas, or even, in three well observed cases, the LISs have expansion velocities lower than that of the surrounding nebula. Both the stagnation zone model and the jet models predict high expansion velocities, so they fail to explain these low-velocity knots, unless they have been completely slowed down by interaction with the surrounding gas[4]. Moreover, the high degree of symmetry of these low-velocity knots also excludes their formation via in situ instabilities. We are then tempted to suggest that they could represent symmetric knots originating in the AGB wind, which survived till the present age. This would imply a peculiar geometry for the AGB wind. This is an interesting possibility for some objects (e.g. IC 2553, Corradi et al. 2000b; and the others for which the low-velocity pairs are located outside the rims, i.e. sharing the outer shells expansion), but is unlikely to work for the highly peculiar structures found for instance in Wray 17-1 (cf. Corradi et al. 1999).

Summarizing, the controversy over the presence of well defined bow-shocks at the knots' surface is crucial in order to understand the formation of symmetrical, high-velocity pairs of knots. The low-velocity pairs of knots deserve a different explanation (unless a significant slowing down is invoked), and we argue that in some objects these features might be fossil remnants of symmetrical condensation originating in the AGB wind.

[4]Severe slowing down is expected when the jet is not feeding the knot anymore, and it is mainly caused by the decrease of the knot's density, that follows its expansion once the knot becomes ionized (Soker & Reveg 1998).

6. Non-symmetrical LISs

Table 5 lists the known PNe associated with non-symmetrical LISs, i.e. both isolated knots and systems of non-symmetrical knots or filaments (the latter sometimes radially aligned with the central star). Some of these PNe have well studied LISs, like the cometary knots of NGC 7293 (O'Dell & Burkert 1997; Meaburn et al. 1998) or the high-velocity knots of MyCn 18 (Bryce et al. 1997; O'Connor et al. 2000).

The formation of most isolated/non-symmetrical LISs can be understood by assuming different in situ dynamical and/or radiative instabilities and other processes that can create inhomogeneities in the mass outflow, such as condensations created during the pre-PN stage. The two types of processes – i) Rayleigh–Taylor, Kelvin–Hemholtz and Vishniac instabilities (Dyson, Hartquist & Biro 1993; García-Segura & Franco 1996), and ii) fossil AGB condensations – would produce structures which do not show highly peculiar velocities as compared to those of the shells in which they are embedded. This might be the case for IC 4593, Hu 2-1, NGC 7662, NGC 5882 and NGC 6337.

In addition, if resulting from dynamical instabilities during the fast vs. slow winds interactions, the structures will appear at the edges, or departing from, the bright rims of the PNe. Only three PNe in Table 5 show this kind of LIS (NGC 7293, NGC 6326 and NGC 6337), whereas most objects (14 over 17) appear well *outside* the rims, often associated with the outer shells (IC 4593, NGC 7662, NGC 2392, NGC 3242, NGC 5882, and probably NGC 6818, NGC 7354 and IC 4637). It is nowadays believed (Marten

& Schönberner 1991; Mellema 1994) that the dynamical structure of the attached shells of PNe is driven by the expansion of the ionization front. Thus, the above facts would indicate that the majority of the isolated LISs are not produced by dynamical instabilities related to the action of the fast post-AGB wind.

Five PNe in Table 5, however, possess high-velocity structures. This raises a problem when trying to explain the formation of these LIS as above. Radiation instabilities can modify/exacerbate such structures, and the ionization process itself can increase the LIS velocity substantially (the "rocket effect"; Mellema et al. 1998). So, these LISs might be structures previously formed that were later accelerated by the rocket effect. Again, while this might apply to some of the PNe in Table 5 (NGC 3242 and NGC 2392 being the best cases), it is very unlikely that it can for instance explain the very high velocities (≤ 500 km s^{-1}) of the system of knots of MyCn 18 (Bryce et al. 1997), which furthermore show the same linear increase of velocities with distance as several jets discussed in Section 4.2.

Other models proposed to explain the formation of non-symmetrical LISs invoke in situ instabilities caused by the interaction of the expanding AGB wind with a non-homogeneous medium. In fact, Dgani & Soker (1997, 1998) and Soker & Zucker (1997) discussed the interaction of the PN with the magnetized interstellar medium, showing that Rayleigh–Taylor and Kelvin–Hemholtz instabilities could fragment the outermost shell (the halo) producing holes, which in turn allow the penetration of interstellar material into the internal regions of the nebula. They argue that such interstellar clumps would appear as low-ionization knots, and if this is the case, we would expect velocities generally smaller than that of the shell in which they are embedded. Thus, noting that only one of the PNe in Table 5 has isolated LISs with lower expansion velocities than the main nebula, interstellar clumps are not likely as an explanation for the formation of isolated structures.

In summary, we find that in situ instabilities and/or fossil condensations due to an inhomogeneous AGB wind are the primary origin of isolated LISs. Most of them are located in the outer shells of the PNe and therefore are not related to the action of the fast post-AGB wind, but to the dynamical and radiative evolution of the AGB slow wind.

7. On PNe showing multiple pairs of LISs

Several PNe in Table 1, namely IC 4634, Hb 4, NGC 6309, M 3-1, K 1-2, Wray 17-1, IC 2553, NGC 5189 and He 2-141, show pairs of LISs which appear to be roughly perpendicular to each other. Note that this property appears in all the classes of LISs discussed in this paper (jets, jet-like features and pairs of knots), adding another complex piece to the puzzle of the formation of these low-ionization components of PNe.

One may argue that a combination of some of the models previously discussed could be at work. For instance, the formation of jets by accretion-disks (i.e. before the PN main bodies) may be followed by the ISW evolution, which in turn originate a pair of knots in the polar direction of the main shell, i.e. not necessarily in the direction of the jets. The simulations of Blackman et al. (2000), on the interplay between MHD disk winds vs. MHD stellar winds, result in a different axis for the jet and the nebula, with sometimes very large angles (up to 90 degrees) between the collimated systems, as observed in some real PNe. Unfortunately, neither the PNe mentioned at the beginning of this section have sufficiently good data, such as information on the deprojected orientation of the various collimated structures, nor are the simulations by Blackman et al. (2000) sufficiently detailed to allow a formal comparison. The other possibility of an extreme precession of the main nebular axis or of the disk appears unlikely, as mentioned in Section 4.2.

8. Conclusions

We have studied the 50 PNe presently known to contain low-ionization structures and compared their morphological and kinematical properties with the predictions of current theoretical models. The main results of this study are the following.

1 - Low-ionization structures are present indistinctly in all morphological classes of PNe, indicating that their formation is not necessarily connected with the processes responsible for the asphericity of the main morphological components of PNe.

2 - Only a few of the observed low-ionization *jets* could be formed by the HD and MHD interacting stellar winds (NGC 7009, NGC 6891 and NGC 3918), the latter ones being favored by the observed linear increase of the expansion velocity along the jets. Other jets (K 4-47, M 1-16 and Fg 1) can be better understood adopting accretion-disk jet models. No model appears instead to be able to explain the jets younger than the main PN shells (Hb 4, NGC 6210 and NGC 6543), nor those with very large jet-nebula angles (Hb 4, NGC 6210 and NGC 6884).

3 - A number of *jet-like* structures show velocities that are similar to those of the environment. We have studied five well observed nebulae containing this kind of LIS (IC 4593, He 2-429, NGC 6881, K 1-2 and Wray 17-1) and conclude that none of the existing models can account for them.

4 - Symmetrical pairs of *high-velocity knots* could originate by HD or MHD interacting stellar winds and accretion-disk systems, or at the zones of stagnation of partially collimated winds. Since the related outward-facing bow shocks are generally not observed, their surfaces might have been modified by HD instabilities. Pairs of *low-velocity knots* are in turn less well studied theoretically, and we suggest that some of them might have originated in the AGB wind, implying a very interesting AGB mass-loss geometry.

5 - Isolated LISs may be formed by in situ instabilities as well as by fossil AGB mass loss inhomogeneities. Distinguishing between these processes is not an easy task; however, the position of most isolated LISs indicate that they are not related to dynamical instabilities due to the action of the fast post-AGB wind.

Clearly, further modeling and observations are needed in order to reach a more complete understanding of the physical processes governing the formation of the various types of LISs. In this direction, one of the next steps will be to try a detailed comparison of the physico-chemical properties of LISs with those of the main nebular components, for a broad sample of PNe.

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Table 1

Planetary nebulae showing low-ionization structures

PN name	PN G number	PN morphology[1]	Class of LIS	References[2]
IC 4634	000.3+12.1	P	1 pair of jets, 1 pair of knots	1, 2, 3
Cn 1-5	002.2 −09.4	E	1 pair of knots	2
NGC 6369	002.4 +05.8	E	several filaments	3
Hb 4	003.1 +02.9	E	1 pair of jets, 1 pair of knots	2, 3, 4
NGC 6309	009.6 +14.8	P	1 jet-like pair, 1 pair of knots	2
IC 4593	025.3 +40.8	E	1 jet-like pair, 1 pair of knots and other knots	2, 5, 6
NGC 6818	025.8 −17.9	E	several knots	2
NGC 6751	029.2 −05.9	E	1 jet-like pair	2, 7, 8
PC 19	032.1 +07.0	P	1 pair filaments	9
NGC 7293	036.2 −57.1	E	several knots	10, 11
NGC 6572	034.6 +11.8	E	2 pairs of knots	12
NGC 7009	037.7 −34.5	E	1 pair of jets, 1 pair of knots	13, 14, 15
NGC 6210	043.1 +37.7	P	1 pair of jets	16
He 2-429	048.7 +01.9	E	1 jet-like pair	9
Hu 2-1	051.4 +09.6	B	1 pair knots, 1 isolated knot	17
NGC 6891	054.1 −12.1	E	1 pair of jets	18
He 1-1	055.3 +02.7	P	1 pair of knots	9
K 3-35	056.0 +02.0	E	1 pair of knots	19
NGC 6905	061.4 −09.5	I	1 pair of knots	20, 21
NGC 6881	074.5 +02.1	B	2 jet-like pairs, 1 pair of knots	22
NGC 6884	082.1 +07.0	E	1 pair of jets, 1 pair of knots	23
NGC 6826	083.5 +12.7	E	1 pair of knots	14, 15, 24
NGC 6543	096.4 +29.9	E	1 pair of jets	14, 25
NGC 7662	106.5 −17.6	E	multiple pairs of knots and filaments and some isolated knots	15, 26
NGC 7354	107.8 +02.3	E	1 jet-like pair, isolated knots	3
Kj Pn 8	112.5 −00.1	B	2 pairs of knots	27, 28, 29
K 4-47	149.0 +04.4	-	1 pair of jets	30
IC 2149	166.1 +10.4	-	1 knot	26
J 320	190.3 −17.7	P	1 knot	31
NGC 2392	197.8 +17.4	E	several filaments	31, 32, 33, 34
M 1-16	226.8 +05.6	B	1 pair of jets	35, 36
NGC 2438	231.8 +04.1	E	1 pair of knots	2
NGC 2440	234.8 +02.4	B	1 pair of knots	37
M 3-1	242.6 −11.1	P	1 jet-like pair, 1 pair of knots	2
NGC 2452	243.3 −01.0	I	1 knot, 1 filament	2

Table 1—*Continued*

PN name	PN G number	PN morphology[1]	Class of LIS	References[2]
K 1-2	253.0 +10.1	E	1 jet-like pair, 2 pairs of knots	2, 38
Wray 17-1	258.0 −15.7	E	1 jet-like pair, 1 pair of knots	2, 38
NGC 3242	261.0 +32.0	E	2 knots	2, 15, 26
IC 2553	285.4 −05.3	E	2 pairs of knots	2, 39
Fg 1	290.5 +07.9	P	1 pair of jets	40, 41, 42
NGC 3918	294.6 +04.7	E	1 pair of jets	2, 38
NGC 5189	307.2 −03.4	B	multiple pairs of knots	24, 43
MyCn 18	307.0 −04.1	B	several knots	44, 45
He 2-434	320.3 −28.8	E	1 pair of knots	2
He 2-141	325.0 −04.1	I	2 pairs of knots	2
NGC 5882	327.8 +10.0	E	3 knots	39
He 2-186	336.0 −05.1	P	1 pair of jets	2, 30
NGC 6326	338.2 −08.3	E	several filaments	2
IC 4637	345.4 +00.1	E	2 knots	2
NGC 6337	349.3 −01.1	E	several filaments	2, 30

[1]E= ellipticals; B= bipolars or quadrupolars; I= irregulars; and P= point-symmetric PNe.

[2] 1= Schwarz 1993; 2= Corradi et al. 1996; 3= Hajian et al. 1997; 4= López, Steffen & Meaburn 1997; 5= Corradi et al. 1997; 6= O'Connor et al. 1999; 7= Gieseking & Solf 1986; 8= Chu et al. 1991; 9= Guerrero, Vázquez & López 1999; 10= O'Dell & Burkert 1997; 11= Meaburn et al. 1998; 12= Miranda et al. 1999; 13= Reay & Atherton= 1985; 14= Balick et al. 1994; 15= Balick et al. 1998; 16= Phillips & Cuesta 1996; 17= Miranda 1995; 18= Guerrero et al. 2000; 19= Miranda et al. 1998; 20= Cuesta, Phillips & Mampaso 1990; 21= Cuesta, Phillips & Mampaso 1993; 22= Guerrero & Manchado 1998; 23= Miranda, Guerrero & Torrelles 1999; 24= Phillips & Reay 1983; 25= Miranda & Solf 1992; 26= Balick et al. 1993; 27= López, Vázquez & Rodríguez 1995; 28= López et al. 1997; 29= Vázquez, Kingsburgh & López 1998; 30= Corradi et al. 2000a; 31= Balick 1987; 32= Miranda & Solf 1990; 33= O'Dell, Weiner & Chu 1990; 34= Phillips & Cuesta 1999; 35= Schwarz 1992; 36= Corradi & Schwarz 1993; 37= López et al. 1998; 38= Corradi et al. 1999; 39= Corradi et al. 2000b; 40= López, Roth & Tapia 1993; 41= López, Meaburn & Palmer 1993; 42= Palmer et al. 1996; 43= Reay, Atherton & Taylor 1984; 44= Bryce et al. 1997; 45= O'Connor et al. 2000.

Note that IC 4673 and IC 1297, originally present in the list of LISs of Corradi et al. (1996), are not included in the table since recent spectra taken by us removed the original suggestion that they contain low-ionization microstructures. In particular, the bright knot found by Corradi et al. (1996) inside IC 1297 turned out to be field star.

Table 2

Planetary nebulae with low-ionization jets

Object	Confidence[1]	Kinematical ages[2]	Orientation[3]	Location[4]
IC 4634	L	-	-	outside
Hb 4	H	younger	90°	outside
NGC 7009	L	coeval	30°	outside
NGC 6210	L	younger	90°	outside
NGC 6891	H	coeval	0°	outside
NGC 6884	L	coeval	50°*	outside
NGC 6543	H	younger	20°*	outside
K 4-47	H	older	-	outside
M 1-16	L	older	-	outside
Fg 1	H	older	40°*	outside
NGC 3918	H	coeval	0°	outside
He 2-186	H	-	-	outside

[1]H stands for high and L for low confidence.

[2]Kinematical ages are quoted with respect to the main shell ones.

[3]The approximate angle of the jet with respect to the major axis of the main shell, from polar (0°) to equatorial (90°) jet orientations. '-' is used for the PNe without such a information. '*' indicates that the quoted angle is for the jet precessing axis.

[4]The apparent location of the tip of the jet with respect to the rim, or to the barely resolved core emission in the case of K 4-47.

Table 3

Planetary nebulae with jet-like structures

PN name	Confidence[1]	Kinematical data[2]	Orientation[3]	Location[4]
NGC 6309	L	no	-	outside
IC 4593[a]	H	yes	-	outside
NGC 6751	L	yes	-	outside
He 2-429	H	yes	0°	outside
NGC 6881	H	yes	40°*	outside
NGC 7354	L	no	-	outside
M 3-1	L	no	-	outside
K 1-2	H	yes	-	inside
Wray 17-1	H	yes	-	inside

[1]As in Table 2.

[2]Some of the PNe classified as jet-like LISs do not have kinematical studies for the LISs (those quoted with 'no'). The others are real low-velocity systems highly collimated.

[3]As in Table 2, but for the jet-like axis.

[4]As in Table 2, but for the jet-like LISs.

[a]Harrington & Borkowsky (2000) claim that this highly collimated LIS is a real jet, based on *HST* imaging. Corradi et al. (1997), however, argued that it is unlikely that the very low radial velocities observed in the LIS are just a projection effect.

Table 4
Planetary nebulae with pairs of low-ionization knots

PN name	Confidence[1]	Peculiar velocities[2]	Orientation[3]	Location[4]
IC 4634	L	-	-	outside
Cn 1-5	L	-	-	outside
Hb 4	L	-	-	inside
NGC 6309	L	-	-	inside
IC 4593	H	no	-	outside
PC 19	H	high	-	outside
NGC 6572	H	high/low	-	outside
NGC 7009	H	high	polar	outside
Hu 2-1	H	high	polar	outside
He 1-1	L	no	-	outside
K 3-35	H	-	-	inside
NGC 6905	L	high	polar	outside
NGC 6881	H	-	-	outside
NGC 6884	L	high	-	outside
NGC 6826	L	high	polar	outside
NGC 7662	H	high/low	-	outside
Kj Pn 8	H	high	polar	outside
NGC 2438	L	-	-	inside
NGC 2440	H	no	polar	outside
M 3-1	L	-	-	outside
K 1-2	L	-	-	outside
Wray 17-1	H	low/no	-	inside
IC 2553	H	no	-	outside
NGC 5189	L	low/no	-	inside
He 2-434	L	-	-	outside
He 2-141	L	-	-	inside

[1]As for Table 2.

[2]High (low) corresponds to peculiar velocities higher (lower) than the environment. 'no' stands for the cases in which velocities of LIS do not differ from the ambient velocity, and '-' for the PNe without kinematical data for the LIS. Some PNe have more than one pair of knots with available kinematical data. In these case we use 'high/low' and 'low/no' indicating the kinematical status of two pairs of low-ionization knots.

[3]As for Table 2, but for at least one of the pairs of knots.

[4]As for Table 2.

Table 5

Planetary nebulae with isolated low-ionization structures

PN name	Confidence[1]	Peculiar velocities[2]	Location[3]
NGC 6369	L	-	outside
IC 4593	H	no	outside
NGC 6818	L	-	outside
NGC 7293	H	low/high*	inside
Hu 2-1	L	no	outside
NGC 7662	H	no	outside
NGC 7354	L	-	outside
IC 2149	L	high	-
J 320	L	-	outside
NGC 2392	H	high	outside
NGC 2452	L	-	outside
NGC 3242	H	high	outside
MyCn 18	H	high	outside
NGC 5882	H	no	outside
NGC 6326	L	-	inside
IC 4637	L	-	outside
NGC 6337	H	no	inside

[1]As in Table 2.

[2]As in Table 4, but for isolated LISs.

[3]As in Table 2.